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Measures and Means to Improve the Energy Efficiency of Food Production

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Abstract. Improving the energy efficiency of modern enterprises, including the food industry as one of the priorities for the life support of the population, is of strategic importance for Ukraine. The purpose of the study is an analysis of the energy-saving potential of food industry enterprises and the search for ways to reduce the energy intensity of technological processes, devices, and equipment, as well as transmission heat losses of buildings and structures. For field tests of industrial and technological objects, a combined thermal imaging and thermometric research methodology was chosen, which combines thermal imaging of characteristic thermal zones to detect anomalous areas and contact measurements of thermophysical parameters in these zones. A computerised information and measuring system equipped with a set of primary sensors of temperature, heat flux, humidity, etc. was used for long-term monitoring of thermophysical parameters simultaneously at different sites of the facilities. As a result, an array of data was obtained and processed, the parameters of complex convective and radiation heat transfer were calculated, and the heat transfer resistance was determined, which allows assessing the degree of danger of the detected thermal anomalies and developing measures for thermal modernisation of facilities using modern thermal insulation materials. Reduction of heat loss in production processes is also achieved by organising high-quality thermal insulation of technological apparatuses, pipelines and refrigeration equipment. The main parameter for selecting the required material is its low thermal conductivity in the operating temperature range of the equipment. For the effective heat insulator selection, the thermal conductivity of a number of popular materials of world-famous manufacturers was studied based on the certified information-measuring system of Ukrainian design by the stationary plate method with the use of heat flux and temperature sensors. The thermophysical parameters of heat-insulating materials in the range of 0.02...0.045 W/(m·K) were estimated and thereby revealed the thermal conductivity of materials with a closed microporous structure to be half that of fibrous ones and not dependent on the density of the material, which makes them the best option for high-quality insulation of buildings and equipment of food production

Keywords: energy saving, energy audit, thermal insulation, monitoring, heat transfer resistance, thermal resistance, thermal conductivity

Introduction

The energy supply of the economy and efficient use of fuel and energy resources of Ukraine is one of the main national priorities in terms of its economic significance. The economic condition of each enterprise is determined by its ability to effectively reduce energy consumption. Ukraine's industry, including food and processing, has a

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huge potential for energy and resource saving with the introduction of the latest technologies and equipment, the use of secondary energy sources, as well as the modernisation of obsolete energy equipment, buildings, and structures for industrial purposes.

Leading scientists and economists dedicated their works to the study of energy saving issues in Ukraine, the formation of mechanisms for the implementation of energy saving measures of industrial enterprises, development of an energy efficiency strategy that accounts for the conditions and features of the functioning of energy supply systems of industrial enterprises and will allow solving key challenges of efficient use of energy resources in the long term.

Experts distinguish the following main types of energy-saving measures: organisational, technological and investment [1-3]. The latter include highly effective measures for the transition to alternative energy sources and the use of modern energy-saving production technologies [2], but require higher capital investments, while others are less costly and no less effective.

Organisational measures include internal energy audit and compiling the "Energy passport of the enterprise" developed by the State Committee of Ukraine on Energy Saving according to the Law of Ukraine "On Energy Saving" [4; 5]. The introduction of energy certification offers an opportunity to create an information database on the state of use and reserves of fuel and energy resources and creates conditions for the development of energy-saving measures for the future [3; 6; 7]. Every enterprise, including industrial or agricultural, and its boiler rooms must undergo this procedure once every 5 years.

Ukrainian [1; 3; 6] and foreign experts [8] agree that the basic energy-saving measures are technological. First of all, it is the optimisation of technological processes, replacement or modernisation of outdated industrial equipment, as well as the introduction of energy efficiency standards in the use of industrial buildings and structures. The norms of modern industrial construction already include European requirements for energy saving and energy efficiency, and old enterprises need the so-called "thermal modernisation". Usually, it is a set of measures aimed at increasing the resistance to heat transfer of building envelopes and structures using modern heat-insulating materials, resulting in energy savings and reduction of heat loss [6; 7].

Thermal insulation of production equipment, technological heat and mass exchange apparatuses, vessels and pipelines is also an important part of the complex of energy-saving measures in the food and processing industry [7-9]. Thermal insulation of pipelines, vessels and apparatuses is a mandatory procedure after their strength and density tests. Heat losses from poorly performed insulation works lead to an increase in thermal loads on equipment, violation of thermal conditions of technological processes, and deterioration of product quality. Materials must provide high-quality protection of production equipment and pipelines during temperature and humidity fluctuations, which is especially important in the processes of cooling and cold storage of food products.

Refrigeration technologies are a significant segment of energy consumption in the food industry, because without which any processing of livestock products, food production and its proper storage is impossible [9]. The main aspects of cold insulation measures are:

- insulation of trucks with isothermal vans for perishable products equipped with refrigeration units;
- insulation of refrigerated railway wagons;
- insulation of domestic and industrial refrigerators;
- insulation of pipelines and containers with refrigerants;
- insulation of mobile and stationary freezers for food, special chemicals and other materials.

Cold insulation, like thermal insulation, also contains an energy-saving potential aimed at reducing or preventing the transfer of heat from the environment to an object that is artificially cooled to maintain a negative temperature and vice versa, which can be ensured by the use of efficient low-heat-conducting heat insulators.

The purpose of the study is to determine the transmission heat losses of industrial facilities and equipment of food production and to justify the choice of the most effective heat-insulating materials for their maximum reduction.

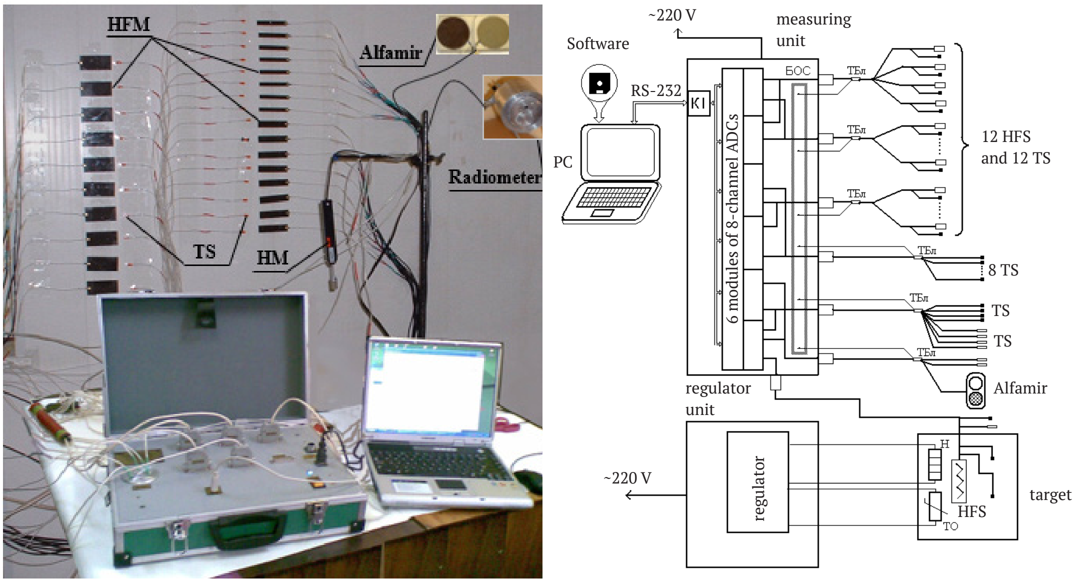
Materials and Methods

1. Determination of heat transfer resistance of multilayer enclosing structures of industrial buildings and structures, power equipment, energy-intensive equipment and technological apparatuses.

The traditional method for determining transmission heat losses is a calculation method based on the average annual temperature of the object and the environment and empirical coefficients. Such a method is approximate and gives a generalised notion of the actual state of the object. Real results can be obtained only by long-term monitoring of the thermal state of the object in in-situ conditions, followed by processing the obtained data array.

The most modern method of such studies is the combined thermal imaging and thermometric method [6; 7], recommended by regulatory documents [4; 10]. At the first stage, thermal imaging of the elements of enclosing structures (ES) of buildings, structures or equipment is carried out, based on the results of which the images of temperature fields are analysed to determine the zones of thermal anomalies. The next step is to study the thermal protection properties of the ES using a wide range of devices to determine a number of characteristic parameters: the temperature of the ES surfaces and the environment, the density of heat flux through the ES and from energy sources, air humidity and materials, air velocity, heat exchange coefficients. At the same time, the use of a number of separate devices can lead to a multiplication of the total measurement error and is technically and economically unprofitable.

ES of objects usually consist of various structural elements with different thermal resistance, so for surveys and qualitative assessment of heat loss, it is necessary to conduct long-term monitoring of the thermal state of the structure or apparatus, while simultaneously measuring and recording the values of temperature and heat flux density in several dozen characteristic and abnormal areas. Therefore, to conduct synchronous and long-term studies, it is advisable to use an information-measuring system, which is presented in Figure 1, the computerised system "RESOURCE" [7], developed for the complex instrumentation support of the research of objects' ES according to the methods of standards [4; 10].



a) b)

Figure 1. Appearance (a) and functional diagram (b) of the information-measuring system "RESOURCE": HFS – heat flux sensors (transducers); TS – temperature sensors (transducers), HM – humidity meter (sensor), PC – personal computer

"RESOURCE" is a multichannel measuring system that allows determining the density of the heat flux, the temperature of the surface and the air near it at many different sites of the object under study, humidity, thermal conductivity, heat transfer coefficient and components of the heat flux in complex heat exchange and calculating the value of transmission heat losses on the surface of the object in production and laboratory conditions.

The system is fully equipped (Fig. 1) with:

– specialised heat flux sensors HFS and temperature TS in quantities determined by the relevant regulatory documents [4; 10] for heat engineering tests of construction objects;

– radiometer – absolute cavity receiver of hemispherical thermal radiation for non-contact measurement of thermal radiation flux density;

– "Alfamir" devise for the determination of convective and radiative heat transfer coefficients and flow components in complex heat transfer, which is a flat structure of two HFSs on a common isothermal substrate, with thermocouples for measuring the temperature of the substrate and adjacent air. Free surfaces of both HFSs have contrasting degrees of blackness, the range of values of which is from 0.85 to 0.90 for black and from 0.02 to 0.25 for white HFS;

– the primary air humidity sensor HM.

Specialised measuring devices, such as Fluke, are used for thermal imaging and non-contact temperature measurements [11]. To simultaneously measure the thermal conductivity of the material of the structure, a portable probe express thermal conductivity meter can be connected to the system [7].

Main technical characteristics of the resource system:

– range of measured values of surface heat flux density from 10 to 500 W/m^2;

– basic permissible relative error of measuring the surface heat flux density ± 4%;

– measured temperature range from minus 40 °C to +50 °C;

– the main permissible absolute error of temperature measurement is ±1 K.

When surveying natural objects, their individual characteristic zones can be located at a considerable distance – up to several tens of meters, which necessitates the use of a distributed measuring system with several modules. To monitor the thermal condition of such objects, a modified measuring system "RESOURCE-RC" with a radio communication channel between the modules (Fig. 2) and the central control unit was developed.

Figure 2. Multichannel measuring module "RESOURCE-RC"

Each measuring module can be connected to eight primary sensors of different types, and it is powered by a built-in 12 V battery. Low-power transceivers with a capacity of up to 10 mW, which do not require special permission, are used to transmit data over the radio channel. Each module, working separately, collects measurement data from its sensor group and discretely transmits it to the central control unit, where it is processed in the software environment.

Primary heat flux sensors are bimetallic converters of the auxiliary wall type according to DSTU 3756-98 [12]. The visual appearance of the specialised HFSs is presented in Figure 3 in several modifications that account for the specific features of the surveyed objects and can be mounted on different types of structures. Primary temperature sensors are represented by a set of standard thermoelectric transducers the THC(L) type [13] and resistance thermometers Pt-100 [14].

Figure 3. Measuring sensors of various modifications (a) and their installation during field tests on the inner surface – heat flux sensors (b); on the outer surface – temperature sensors (c)

Data on the thermal regime of the inspected building structure or equipment is converted by primary sensors into analogue electrical signals and submitted to the input of the electronic unit, where they are sequentially registered. The electronic unit is designed as a portable case, and has slots for connecting primary converters and a computer communication interface. The unit also contains a built-in device for stabilising the reference junctions of differential thermocouples, the temperature of which is taken into account in calculations. Depending on the system modification, the number of DC voltage measurement channels in the measuring unit varies from 32 to 96. The measurement results are transmitted to the data acquisition and processing system and converted into heat flux density and temperature in the appropriate units (W/m^2 and °C/C). The duration of continuous recording of research results can vary up to 3-5 days depending on the number of measuring channels and the amount of RAM of the system.

The computing programme of the RESOURCE system allows creating individual configuration files for each monitored object and defining the order of channel polling, time intervals and frequency of polling, exchange rate and computer port number. During operation, signals are measured according to a given programme, and their primary processing and visualisation are performed both tabularly in numerical form and in the form of functional graphs. At the same time, the data is stored in an MS Excel file, which makes it possible to further process it if necessary.

2. Study of thermal resistance and coefficient of effective thermal conductivity of thermal insulation materials.

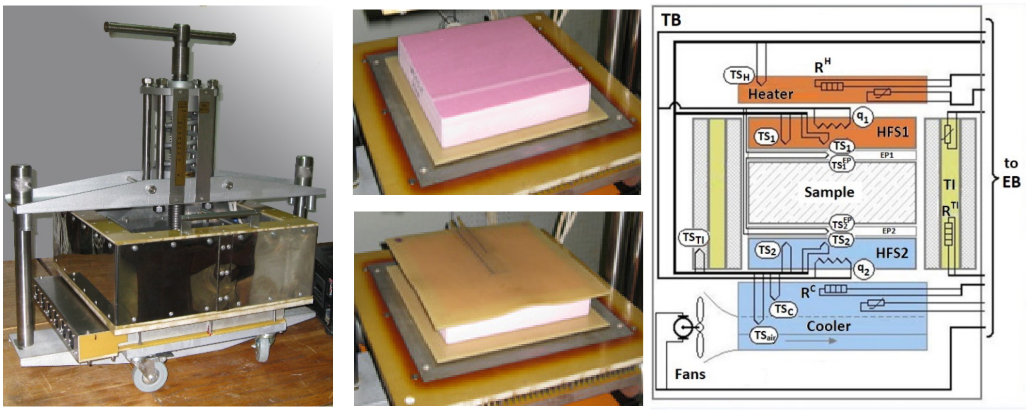
Materials based on foamed rubber, foamed polyethylene, and mineral wool are recommended for the insulation of food-grade industrial equipment. Less often, shells made of polyurethane foam and expanded polystyrene are used [15]. The selection of material depends on the operating conditions of the facility, safety requirements, manufacturability, and cost-effectiveness of installation work, but the main requirement is low thermal conductivity of the material in the range of operating temperature of the equipment.

Mineral wool and expanded polystyrene are traditionally considered the cheapest and easiest to install. However, in practice, they are effective only for insulation of equipment operating at temperatures above 0 °C, because in aggressive conditions of fluctuations in temperature and humidity and condensation at negative temperatures, mineral wool insulators lose their properties. foam polystyrene can be inhabited by rodents, which is not consistent with the high hygienic requirements for the storage and transportation of food products.

Therefore, the insulation material must be non-porous or contain only closed pores, be eco-friendly, resistant to corrosion, fungal formation, and rodent damage. All these qualities are characteristic of polyurethane foam (PU foam), which is obtained from polyurethanes by foaming by the reaction of two liquid components – isocyanate and polyol in the presence of catalysts, emulsifiers, and other impurities, resulting in the formation of microcapsules filled with filler gas. PU foam is applied using a low-pressure device in several layers to achieve the desired thickness for thermal calculations of the object, the foam hardens, forming a dense, uniform and sealed thermal insulation layer that does not require an additional vapour barrier. Sandwich panels based on PU foam are commonly used for the construction of industrial facilities, in particular, warehouses-refrigerators for long-term storage of food products, mobile and stationary freezers, etc.

The Ukrainian market of heat insulators is constantly expanding through both import and domestic manufacturers offering a wide range of products. The main indicators of the effectiveness of thermal insulation materials are their thermophysical characteristics: thermal resistance, which depends on the thickness of the material, and the coefficient of effective thermal conductivity, which has a clearly defined temperature dependence. Measurement of thermal conductivity of thermal insulation materials in Ukraine is regulated by a number of state and international standards [16-18].

Since most thermal insulation materials are non-homogeneous (including fibres, cavities, etc.), according to the current standards, the dimensions of the test samples of materials should be at least 250×250 mm in plan, while the measurement error should not exceed ± 3%. To conduct the research, we used a specialized information-measuring system (Fig. 4) developed in Ukraine, which implements a symmetrical scheme of the thermometric method using two identical primary heat flux sensors [19; 20] and embodies a modern standardised approach to ensuring the necessary requirements for the accuracy and reproducibility of measurement of thermophysical parameters and quantities [21].



a) b) c)

Figure 4. Information and measuring system: a) external appearance of the heating unit; b) placement of samples in the measuring cell; c) functional blueprint

The main element of the information and measurement system is a thermal unit (Fig. 4, a), in which a sample of the test material is placed (Fig. 4, b) with the necessary temperature and thermal conditions provided (Fig. 4, c). The system is also equipped with a device for temperature control of the thermocouple reference junctions. All primary measurement information is accumulated and processed in an electronic unit containing means for regulating thermal conditions, receiving, and processing data and transferring them to a computer for further processing in a specialised software environment. Measurement of thermophysical characteristics of samples of construction and thermal insulation materials can be carried out on samples up to 120 mm thick with maximum performance and standardised accuracy in accordance with the requirements of national and international standards. Main technical characteristics of the system:

– range of values of the thermal conductivity coefficient 0.02...3.0 W/(m·K);

– limits of permissible basic relative measurement error ±3%;

– operating temperature range of -40 °C...180 °C;

– the sample size is 300×300×(10...120) mm.

When preparing samples for the study, they are given a shape suitable for placement in the measuring cell: hard samples are ground to give the working surfaces a plane-parallel shape, and for soft and fibrous ones, additional equipment is made – spacers or a limiting frame. Before placing the samples in the measuring cell of the thermal unit, they are measured and weighed to calculate their density.

According to the standardised procedure [16], measurements are carried out on at least three samples of the same material in a dry state at average temperatures of 10 °C and 25 °C, or in the entire operating temperature range, depending on the purpose of the experiment. Calculations of the coefficient of thermal conductivity are carried out according to standard dependences based on the average results of measurements of temperature, heat flux density and sample thickness [16; 17; 19]. The final result is calculated as the arithmetic mean for the tested samples, considering the measuring error of ±3%.

Results and Discussion

1. Determination of heat transfer resistance of multilayer enclosing structures of buildings, structures, power, and technological equipment

The combined thermal imaging and thermometric method was successfully tested in the study of building structures [22] and was included in the regulatory document [10]. Figure 5 demonstrates the results of a thermal imaging survey of the facade of the two-storey building by Fluke [11], conducted as part of a preliminary examination of its thermal condition.

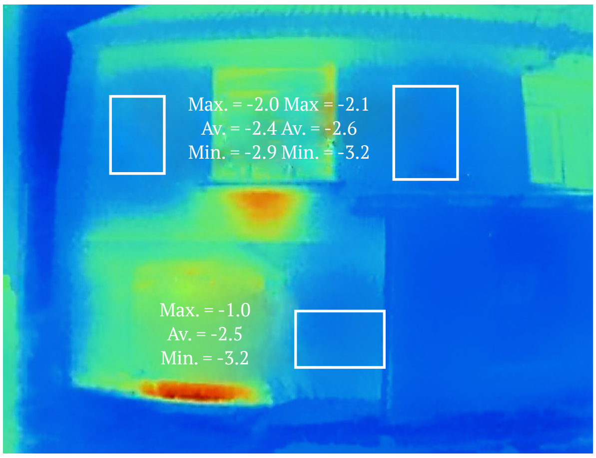


Figure 5. Thermogram of the facade of a two-storey administrative building

The study was conducted during the heating season, and the results of the thermogram analysis accurately identify areas with increased heat loss. The measuring sensors of temperature and heat flux (Fig. 3) of the "RESOURCE" system were installed on such zones outside and inside the building and the thermophysical parameters of the characteristic part of the object were monitored for a certain period of time. The measurement results are shown in Figure 6.

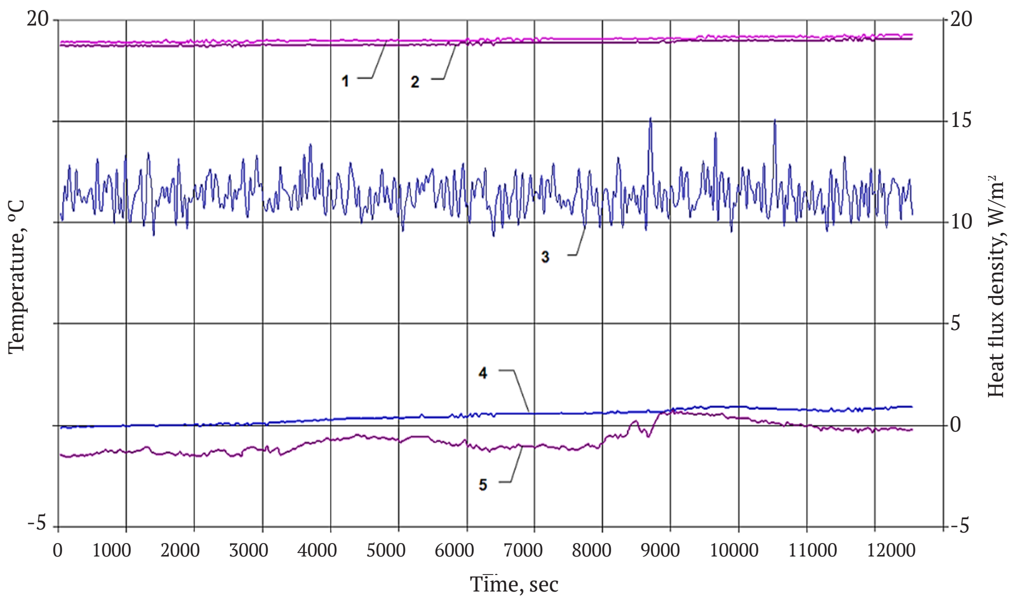


Figure 6. Record of thermophysical parameters for a characteristic area of an object (wall): 1 – internal air temperature; 2 – internal surface temperature of the object; 3 – density of heat flux through the research object; 4 – temperature of the external surface of the object; 5 – outdoor air temperature

The result of the observations is an array of data on the change of thermophysical parameters in real time, which can be further processed according to the relevant standardised methods [4; 7; 10], determining the necessary parameters, analysing, and providing an expert opinion. During quantitative analysis, the actual values of the main heat engineering characteristics of the ES are determined and compared with the values of transmission heat losses obtained by the calculation method. This makes it possible to assess the degree of danger of detected thermal anomalies for the normal functioning of the surveyed objects. Significant defects, assessed by the level of thermal resistance, are considered to be those that lead to a local decrease in thermal resistance by more than 15%.

The combined thermal imaging-thermometric technique can be effectively used in the inspection and determination of heat transfer resistance not only of multilayer enclosing structures of buildings and structures but also of power units and industrial apparatus of food enterprises. The use of the information-measuring system "RESOURCE" for such studies has the following advantages:

– the ability to conduct continuous synchronous observations of the thermal state of objects at several characteristic points for a long time (up to 3-5 days) without stopping the technological process;

– high metrological level of measurements in real conditions, automation of processing and documentation of results;

– ability to conduct an energy audit and take energy-saving measures, in particular, carry out thermal modernisation of industrial buildings or perform thermal insulation of technological equipment, choosing the optimal material.

2. The results of thermal conductivity studies of modern thermal insulation materials are presented in Table 1 at temperatures of 10 °C and 25 °C and graphically in the operating temperature ranges – in Figure 7.

Table 1. *Coefficients of effective thermal conductivity of heat insulators*

No	Material name	Material density, kg/m³	Thermal conductivity coefficient, W/(m·K)
1	IPN-nano KINGSPAN [23]	32 … 35	0.019…0.021
2	Polyurethane foam “ELASTOPOR” [24]	40 … 45	0.020…0.022
3	ISOVER mineral wool [25]	10 … 13	0.037…0.040
4	Expanded polystyrene	35 … 38	0.038…0.042

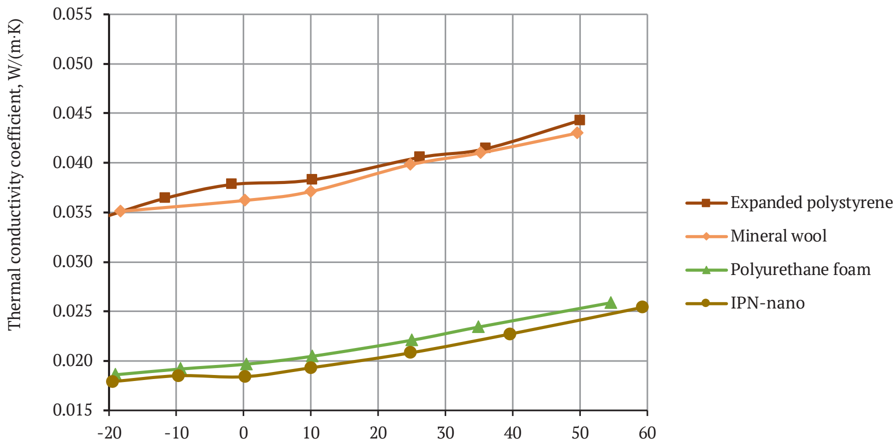


Figure 7. Temperature dependences of thermal conductivity coefficients of modern heat insulators

The values given in Table 1 correspond well with the results of certification tests of established materials [24; 25], while for the newest material IPN-nano [23] the experimental results were obtained for the first time. This material demonstrates high thermal insulation qualities, now it is used mainly as a filler for sandwich panels for the construction of industrial refrigerators-warehouses and modern refrigeration and logistics complexes.

According to Fig. 6, it is possible to select the material that will best meet the requirements for the operation of technological equipment or pipelines in a wide temperature range. The results of the research confirm the high thermal insulation properties of polyurethane foam, which, along with operational and hygienic properties, makes it one of the leading effective heat and cold insulation of refrigerators and freezers, especially for complex-shaped structures.

Conclusions

Solving the issue of energy saving in the food industry requires a comprehensive approach to identifying and eliminating sources of heat loss. The procedure includes inspection and evaluation of thermal parameters of structures of buildings and equipment, and, if necessary, carrying out measures for thermal modernisation of industrial buildings and structures, industrial and power equipment using high-quality thermal insulation.

A modern approach to research of the thermal state of objects is provided by a combined thermal imaging and thermometric technique, and modernisation of testing of enclosing structures of buildings and apparatuses in characteristic zones is provided by the use of a multi-channel information and measurement system equipped with various sensors and devices. Such a system allows long-term monitoring simultaneously at many points of the object in automatic mode, which significantly increases the accuracy of research and eliminates the subjective influence of the operator, conducting energy audits and certification of industrial buildings and structures in accordance with the requirements of regulatory documents and develop the necessary energy saving measures, choosing the most optimal material for this.

The main characteristic that confirms the quality of the insulation material is the coefficient of effective thermal conductivity. The study of the thermal conductivity of modern materials on a certified information-measuring system in a wide range of temperatures confirms the high thermal protection properties of polyurethane foam 0.020…0.022 W/(m·K) and IPN-nano 0.019…0.021 W/(m·K). These materials not only provide protection in conditions of temperature and humidity fluctuations, but also meet the requirements of industrial sanitation, which makes it possible to use them for heat or cold insulation of technological devices, pipelines, and equipment of food production. More traditional materials – mineral wool and polystyrene – have almost twice worse thermal conductivity but are more cost-effective in the thermal modernisation of industrial buildings and structures for various purposes.

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Заходи і засоби підвищення енергоефективності харчових виробництв

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Анотація. Підвищення енергоефективності сучасних підприємств, в тому числі харчової галузі як однієї з пріоритетних для життєзабезпечення населення, має стратегічно важливе значення для України. Метою дослідження є аналіз потенціалу енергозбереження підприємств харчової промисловості та пошук способів зниження енергоємності технологічних процесів, апаратів та обладнання, а також трансмісійних тепловтрат будівель і споруд. Для натурних випробувань промислових та технологічних об'єктів обрано комбіновану тепловізійно-теплометричну методику досліджень, що поєднує тепловізійну зйомку характерних теплових зон для виявлення аномальних ділянок та контактні вимірювання теплофізичних показників в цих зонах. Для проведення тривалого моніторингу теплофізичних параметрів одночасно на різних ділянках об'єктів використано комп'ютеризовану інформаційно-вимірювальну систему, оснащену комплектом первинних сенсорів температури, теплового потоку, вологості та ін. В результаті отримано і опрацьовано масив даних, розраховано параметри складного конвективного та радіаційного теплообміну, визначено опір теплопередачі, що дозволяє адекватно оцінити ступінь небезпеки виявлених теплових аномалій та розробити заходи з термомодернізації об'єктів із застосуванням сучасних теплоізоляційних матеріалів. Зменшення тепловтрат у виробничих процесах також досягають шляхом організації якісної теплової ізоляції технологічних апаратів, трубопроводів, холодильного обладнання. Головним параметром для вибору необхідного матеріалу є його низька теплопровідність в діапазоні робочої температури обладнання. Для коректного вибору ефективних теплоізоляторів проведено дослідження теплопровідності низки популярних матеріалів відомих світових виробників на сертифікованій інформаційно-вимірювальній системі української розробки стаціонарним методом пластини з застосуванням сенсорів теплового потоку та температури. Оцінено теплофізичні показники теплоізоляційних матеріалів в діапазоні 0,02...0,045 Вт/(м·К) та показано, що теплопровідність матеріалів із закритою мікропористою структурою вдвічі менша за волокнисті і не залежить від густини матеріалу, що робить їх найкращим варіантом для спорядження високоякісної ізоляції будівель та обладнання харчових виробництв

Ключові слова: енергозбереження, енергоаудит, теплоізоляція, моніторинг, опір теплопередачі, тепловий опір, теплопровідність